



**KERNFORSCHUNGSANLAGE JÜLICH GmbH**

Forschungsgruppe Wirtschaft, Energie, Investitionen

**Trend Analysis of Boiler Explosions  
Aboard Ships**

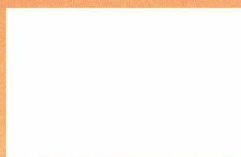
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D. C. Bull, H. J. Hoffmann, K. O. Ott

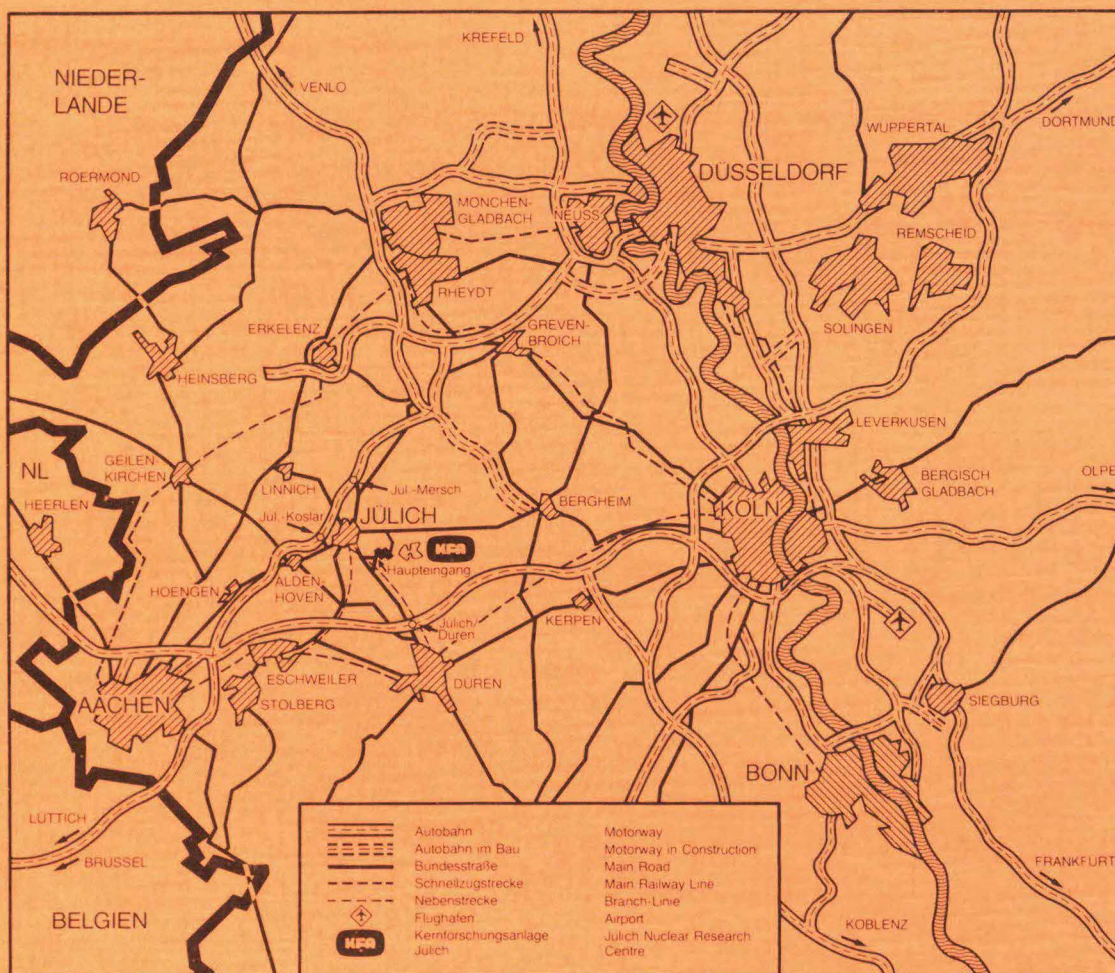
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# **Trend Analysis of Boiler Explosions Aboard Ships**

by

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April 1984

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## ABSTRACT

The historical development of steam boiler technology aboard steam- and later motor-ships is reviewed, setting the stage for statistical investigations of longer term trends in the frequency of boiler explosions.

Two different measures of the safety performance have to be addressed in such an analysis:

- The explosion rate per ship- or boiler-year in an entire fleet, and
- the failure ratio, i.e. the probability that a boiler of a certain vintage suffers an explosion during his useful life.

The major obstacle for both analyses, the distortions due to statistical fluctuations, have been dealt with by applying a special smoothing procedure. The failure ratio analysis requires further an estimation of failures to be statistically expected in the future; this is accomplished by means of a previously developed methodology. This paper is primarily concerned with the statistical analysis of boiler explosion data. The methodology is published elsewhere.

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## I. INTRODUCTION

The technology of steam raising aboard ship is an example of an area with a long historical basis and a wide statistical span. Despite the advent of the motor ship steam ships are still in widespread common use today and continue to be built in large numbers.

The fact that seafaring has always been a risky business and recognised as such led at a very early stage to the development of the classification societies, notably Lloyd's and Det Norske Veritas. The records of these institutions provide a very comprehensive data base for the number of ships at sea over the years as well as for accident occurrence within some categories. In the development of the marine boiler there is no doubt that the watchful eye of the insurers has had a benign influence tending to ensure a relatively rapid evolution of safety in this case. This improving safety is reflected in reduced chances for boiler explosions.

Data on major failures, such as boiler explosions, are often plagued by considerable statistical fluctuations which hamper the determination of a clear trend. Recently refined data analysis methods have been developed that address two trends of interest in the context of an evolution of safety:

- trend of the failure rate per operation year as function of time ( $t$ ) (Refs. 1, 2, and 3);
- trend of the chance of a failure per unit as function of the construction year ( $t^C$ ), the so called "failure ratio." This latter trend analysis includes the evaluation of the age ( $\tau$ ) dependency of the occurrence of failures (Ref. 4).

The subject of this paper is the application of these methods to boiler explosions aboard steam ships. Two sets of data have been analysed:

The first set of data is for British steam ships, for which boiler explosions had to be registered according to the "Boiler Explosions Acts" of 1882 and 1890. Summaries of the detailed information are available

in Ref. 6. The information on the British steam ship population as needed for this analysis was made available for this study by Lloyd's Register of Shipping (Ref. 7).

The second set of data covers an international ship population, as listed in Lloyd's Register, with boiler explosions from 1960 through 1981 (Ref. 8). The corresponding population size is given in the same reference.

A preliminary discussion analysis of these data is presented in Ref. 9.

## II TECHNOLOGICAL DEVELOPMENT

### Survey of Historical Development

The main problem which faced all early steam engineers was the design and construction of a closed vessel capable of producing steam at a constant, relatively low, pressure of between 0.2 and 0.35 bar. The materials available in the early days were: copper, cast iron and wrought iron, but the difficulty of obtaining boiler plates of the required thickness and size as well as that of finding personnel skilled in handling the relatively thick plates severely limited the rate of development at first. Boiler design evolved through trial and error. Even as late as the late nineteenth century there were no theoretically formulated rules available to give the pressure vessel designer a sound basis (Ref. 10). The results of the wholly empirical approach coupled with an exponential increase in the number of boilers constructed and a gradual increase in the normal steam working pressures was that over one period the number of boiler explosions increased both in rate and severity.

Whilst land based steam engines have been recorded since 1763 (and other devices powered by steam since the late 17th century) even, another 39 years were to pass before the technology was considered sufficiently proven to be incorporated into a ship.

The first steam ship, powered by a beam engine, was commissioned in 1802. This opened the door to widespread exploitation of the technology and to continual improvements. In 1853, high pressure steam was first introduced into marine applications, and in 1897 a further change in the type of power plant available emerged with the advent of the marine steam turbine. Around the same time various mechanical stoking systems started to be introduced, though manual stoking was never completely eliminated from solid fuel fired marine boilers. Towards the end of the 1930's a slow change over from coal to oil firing of boiler started, which was not to finish completely until the early 1950's. This latter change introduced a whole new category of accident types, discussed in a later section.



Table 1 illustrates the evolution of on-board steam generators in terms of their characteristic technical data for a number of representative steam ships built between 1858 and 1975. The steam pressure increased from 1.7 to 100 bar, the temperature from 130 to 520 °C and accordingly, the thermal efficiency from 4.8 to 33.6 %.

It would be unrealistic to consider the development of the marine boiler as if it took place in complete isolation, naturally land based developments had their influence upon marine engineering and vice versa. That said, whilst land based plant can still be a proving ground for marine application and whilst they originated from the same stem, the special requirements of the marine environment rapidly lead to a major divergence in design characteristics. There are of course several reasons for this, but in the main they all stem from the fact that when all is said and done a ship must float and navigate. It might be said that the marine environment imposed more stringent requirements - indeed it appears on the whole to have lead to more sophisticated and more efficient power plant. A comparison between the size of marine and land based boilers of identical power, (Fig. 1, from Ref. 12) illustrates this point quite well.

In the marine environment the following factors play a role, roughly in this order of importance:

- small size-to-power ratio
- small weight-to-power ratio
- rapid steam raising/cooling
- swift power changeability
- reliability
- easy-to-handle fuel
- universally available fuel

In the land based boiler, size and weight are relatively unimportant, constant non-fluctuating working is generally more important than the ability to make rapid changes, and cheap locally available fuels can often be arranged to be used. Reliability is however often of paramount importance.

Table 1  
(after ref. /11/)

ILLUSTRATING TECHNOLOGICAL DEVELOPMENTS IN STEAM SHIPS  
BY REFERENCE TO STEAM PRESSURE, TEMPERATURE, AND THERMAL EFFICIENCY

Date	Ship	Machinery Type	Steam Pressure bar	Stem Temperature °C	Thermal Efficiency %
1858	Great Eastern	Reciprocating	1.7	130	4.8
1902	Kaiser Wilhelm II	Reciprocating	15.5	203	12.7
1907	Mauretania	Turbine	13.5	197	12.4
1910	Olympic, Titanic	Turbine/recip.	14.8	201	12.7
1929	Bremen, Europa	Turbine	22.5	360	18.7
1942	Examiner	Reheat turbine	83	400	26.3
1956	Caltex Rotterdam	Turbine	41	510	27.1
1967	Idemitsu Maru	Reheat turbine	83	510	31.6
1968	Esso Mercia	Turbine	59	510	30.8
1970	Golar Nichu	Reheat turbine	102	525	33.8
1975	Golar Patricia	Reheat turbine	100	520	33.6

Fig. 1: left: an oil-fired marine boiler;  
right: a pulverized-fuel land boiler of identical output  
(240,000 pound/hour) (after Ref. 12)

Naturally safety is important in both environments. Onshore, a measure of increased safety can be obtained by the old engineering adage of overdesign of the component parts. In the marine context this must however be regarded as an intolerable luxury - no unnecessary weight or volume can be tolerated. A very similar line of considerations has lead to similarly divergent design criteria for ship tankers of oil and liquefied gases compared to land-based storage systems.

To "compensate" for the inability to overdesign, safety margins at sea have been improved by the development of more sophisticated control systems. Thus whilst current boiler management systems are rapidly approaching the electronic era, as recently as 1977 it was observed that the most frequent cause of land based boiler explosions was over-heating through shortage of water - despite the fact that the majority of modern boilers are fitted with automatic water level and firing controls. A note by a U.K. factory inspector concluded that the incidence of damage or explosions is actually higher for fully automatic systems than for manual systems - for management rather than technological reasons! Other frequent causes of failure (Ref. 13) are: overpressure, corrosion, erosion and water-hammer. In the marine environment the frequent changes of working condition as well as the necessity for on-the-spot operatives leads to a much better record on this score. These same frequent changes also result in a reduction in the lifetime of the furnace refractory lining, which in turn means more frequent changes and simultaneously implies more frequent internal inspections. Many potential causes for incidents thus tend to be nipped in the bud.

When it comes to the question of boiler furnace explosions however the balance of safety is quite different. Here we may see the necessarily tightly designed marine boiler as particularly vulnerable.

### Boiler Furnace Explosions

Up until the introduction of oil firing there had been many boiler explosions. The majority of these could be classified as "steam box" explosions, where sudden failure occurred through metallurgical fatigue/ failure in material properties, non-functioning safety or other valves.



In the case of the oil-fired boiler the firebox explosion starts to be the most serious risk. It also has a much greater damage potential in its own right and, by causing secondary failure of containment of the pressure steam side as well can present a formidable incident. At the type of the fuel flow rates associated with normal boiler operation, sufficient fuel can be introduced to a hot furnace, following "flameout" to fill the latter with an explosive fuel/air mixture in a matter of seconds. Boiler furnaces though strong and built to withstand slight overpressures (Ref. 14) are weak indeed against the typical explosion pressures - so much so that to cause rupture only a small fraction of the fire box need be filled with an explosive mixture. To avoid this type of incident, which can only too easily occur, very careful control systems needed to be developed. These include fuel flow control, flame eyes, automatic purging sequencers, automatic igniters etc. etc. Though the state of technological art is such that even a few years ago an extremely reliable fuel management system could have been introduced, this is an area where extreme conservatism still tends to rule the day to some extent. To explain this in part, it is clear that most ships' captains regard the loss of motive power as perhaps the most serious event they are likely to encounter. Who can blame them then for doing their own mental risk-benefit calculation and deciding that they would on balance sooner accept a slightly higher risk of firebox explosion than the risk of power loss following automatic shutdown on a false flame eye indication. Similar reasoning has lead to the relatively slow introduction of all-automatic ignition sequencers, though the risk of inadvertant or deliberate but misintentioned bypassing of sequencing procedures, leading to an increased chance that explosion conditions arise, is thus introduced.

Referring to "oil firing" is an over simplification. In fact the type of fuel is quite critical to the running performance and also to the hazards posed in case of malfunction. Most merchant ships as well as naval vessels used heavy so called residual fuels to fire their boilers at least until the late 1950's. In the case of high firing rate boilers, typical of naval vessels, the fouling problem in many cases reached intolerable proportions, with damaged refractory linings, reduced heat transfer rates and superheater tube failures. In the British Royal Navy in a five year period in the early 60's no fewer than 12 ships had to undergo major surgery as a result of heavy fuel fouling problems. The solution to this problem

for the Royal Navy was to go over to use of distillate fuel. In merchant ships the firing rates are often somewhat lower. Nevertheless there is also a tendency to use distillate fuel for easy start up and/or for auxiliary boilers. Whilst the hot surface autoignition temperature of both heavy fuel oil and distillate fuel are the same, the more volatile nature of the distillate fuel means in practice that it is far easier to arrive at the condition that an explosive fuel/air mixture builds up in a furnace after flame out. This means that precautions which are in any case important for any oil firing system are readily shown to be vital in the less forgiving situation of distillate fired boilers. An alarming example of this point is the fact that following a conversion programme from residual to distillate fuel in the Royal Navy in the 60's a rash of explosions occurred - six in 1968 alone!

### Influence of Regulation Authorities

From the very earliest times the classification societies, as the ships' insurers, have taken what amounts to a regulating line. In addition for U.S. registered ships, the U.S. coastguard has a regulating role. Generally this appears to have had the beneficial role of maintaining and continually upgrading standards. It might, however, be argued that to some extent the existence of norms, standards and codes can restrict the introduction of even safer procedures and technology.

### III. ANALYSIS OF BOILER EXPLOSIONS ABOARD BRITISH SHIPS, 1882 THROUGH 1974

#### Introductory Remarks

The high frequency of "boiler" explosions lead in Great Britain, the country with the largest number of boilers, to the "Boiler Explosions Act 1882" (revised 1890), being "an act to make better provisions for Inquiries with regard to Boiler Explosions." Boiler explosions and failures were then reported annually by the Board of Trade, Ref. 6. These reports contained detailed information on type, application, age and cause of failure, within a prespecified classification scheme, as well as detailed verbal and pictorial descriptions of the damage.

The term "boiler" in the Explosion Act is quite general: it "means any closed vessel used for generating steam, or for heating water, or for heating other liquids, or into which steam is admitted for heating, steaming boiling, or similar purposes." This study, however, deals only with explosions of the "steam generating" system, on British ships, that are subject to the Explosion Act; excluded are "boilers used ... in the Government Service." Main boilers, i.e. boilers for the ship's propulsion, are considered separately.

Although damage description is available in great detail, reliable information on the annual construction rates, that is needed for a statistical analysis, is not available. It can be approximately inferred from changes in the number of registered ships. Another uncertainty results from the number of vessels per ship, that - on the average - is not constant, since technical progress allowed a strong increase in the vessel size.

The number of British steam ships (that have the considered main boilers), and even more so the number of boilers in operation, decreased since the First World War as shown in Fig. 2. For the periods of both World Wars, the information on boiler explosions is incomplete. An interpolation of the failure data was applied to avoid a trend distortion resulting from that lack of data.

number of British steam ships

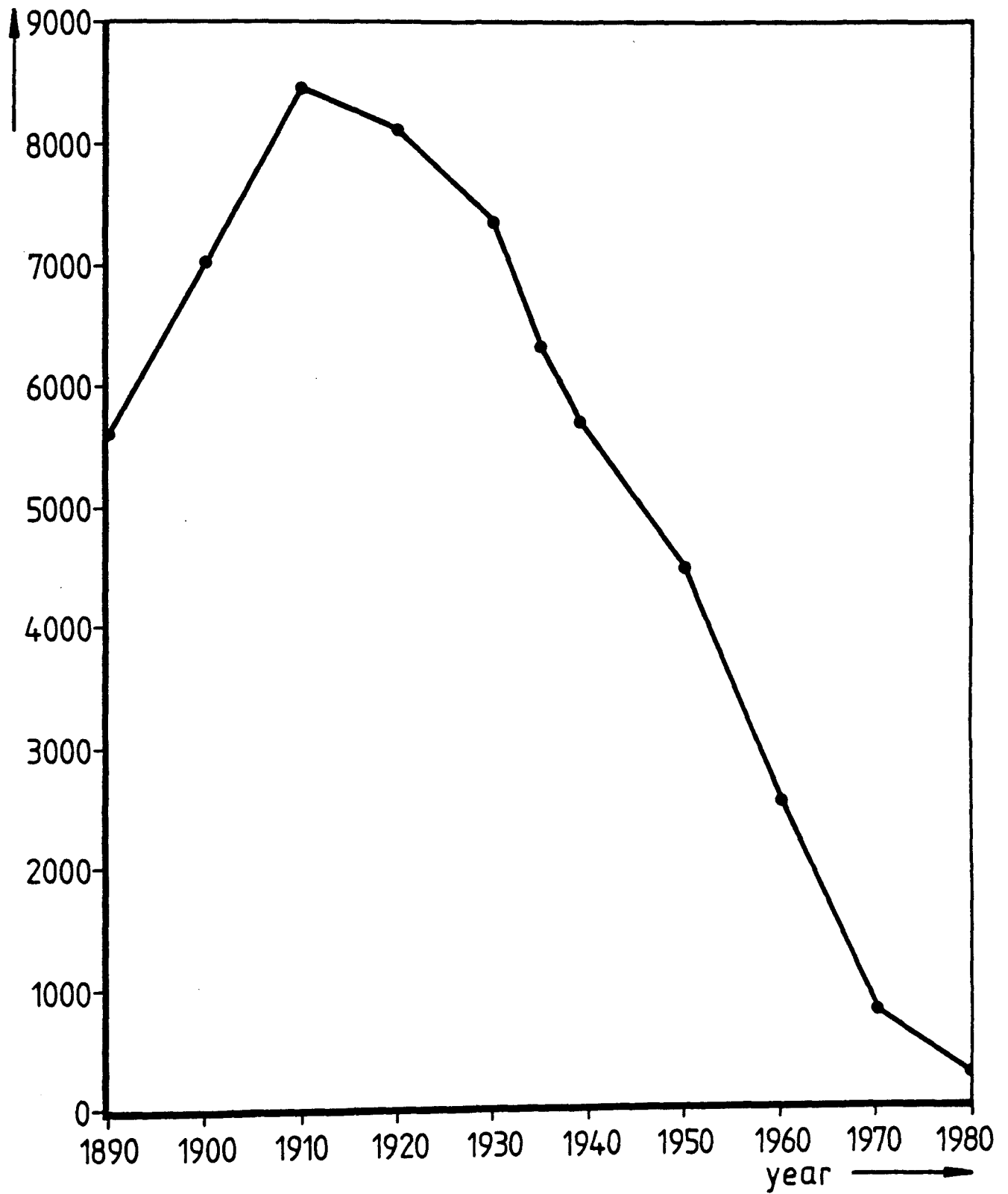


Fig. 2: Number of British steam ships, between 1890 and 1980  
(after Ref. 7)



### Trends of Failure Rates

For the analysis of the long-term trends of the failure rates, the boiler population is considered as a learning system. Failures provide information on possible system deficiencies, and lessons learned from failures should, on the average, lead to an improvement of the system in terms of a declining failure rate. As indicated above, the ship insurers have a benign influence in this direction.

In Refs. 1 and 2, a simple model is developed that associates failure frequencies to the individual failure modes. The overall failure rate is the sum of all individual frequencies. The learning that follows a specific failure event appears as a subsequent reduction of the respective frequency, possible even for an entire class of boilers. A refinement of the model in Ref. 3 also allows a search for a possible increase in failure rates as it might follow the rapid introduction of an insufficiently proven technical feature. Although several temporary increases in failure rates are historically indicated as discussed above, no attempt is made here to quantitatively analyze such short term trends. The emphasis is on the quantification of the longer term trend for which a learning process can be assumed throughout. The failure data are at first expressed as temporal spacings between successive failure events in terms of operation years of the population (i.e. time interval times the average number of operating units). These spacing data are then subjected to a regression procedure where the overall improvement through learning is expressed as a monotony constraint condition. If the failure-event spacings actually increase a monotonously declining failure rate is directly established. The ever present statistical fluctuations that appear as incidentally short failure-event spacings, are converted in this regression procedure in stretches of seemingly constant failure rate; the decrease in the failure rate is then "held up" over those periods. An actual decrease is not discernible during these times.

The elimination of these fluctuations in a mathematically consistent manner is achieved by the "isotonic regression" procedure (Ref. 15) that identifies quantitatively the underlying monotonous trend. The procedure is first applied to the spacings, yielding an increasing sequence. Its subsequent inversion then yields a monotonously declining failure rate.

Figure 3 shows the failure rate trend for the boiler explosions listed in Ref. 6, smoothed by the isotonic regression procedure, in terms of failures per ship-operation year (the ship population is from Ref. 7). Thus, Fig. 3 portrays the rate of explosive failures of the "steam generating systems" of this ship, which may consist of several boilers.

Also depicted in Fig. 3 is the 90 % confidence band around the isotonic regression values that indicates a high statistical significance of the identified trend. The 90 % confidence band is calculated for each individual frequency value that is obtained from the isotonic regression, without taking into account the order restriction of the isotonic regression procedure (comp. Ref. 3). Accounting for this order restriction would generally decrease the confidence band, especially the relatively large confidence band spread for the intervals with only one or a very few failures.

The statistical significance of a trend over a certain time period is derived from the notion that the confidence intervals at the beginning and at the end of that period should be well separated; if the confidence intervals would overlap strongly, a possibly indicated trend would not be significant. Apparently, the assessment of the significance of a trend depends on the definition of the confidence interval significance as well as on the degree of separation. If a 90 % interval is applied, the trend, i.e. a change in failure frequency, is assessed on the 90 % level.

Figure 3 indicates a significantly declining trend for the comparison of the periods 1890 - 1900 and the subsequent one, 1900 - 1938, not however within these two periods. After 1938, there appear several periods with a significant trend: the eventual failure frequency is at least an order of magnitude below the values prevailing toward the end of the previous century.

The good data base allows a statistical analysis of "components" of the steam-generating system:

Of the 1340 explosions in the period 1890 through 1974 that are analyzed above, 845 occurred in main boilers and 162 in auxiliary boilers. Most of the remaining failures occurred through vibration induced rupture of the main steam pipe (187) and as explosion of a stop valve (58). The

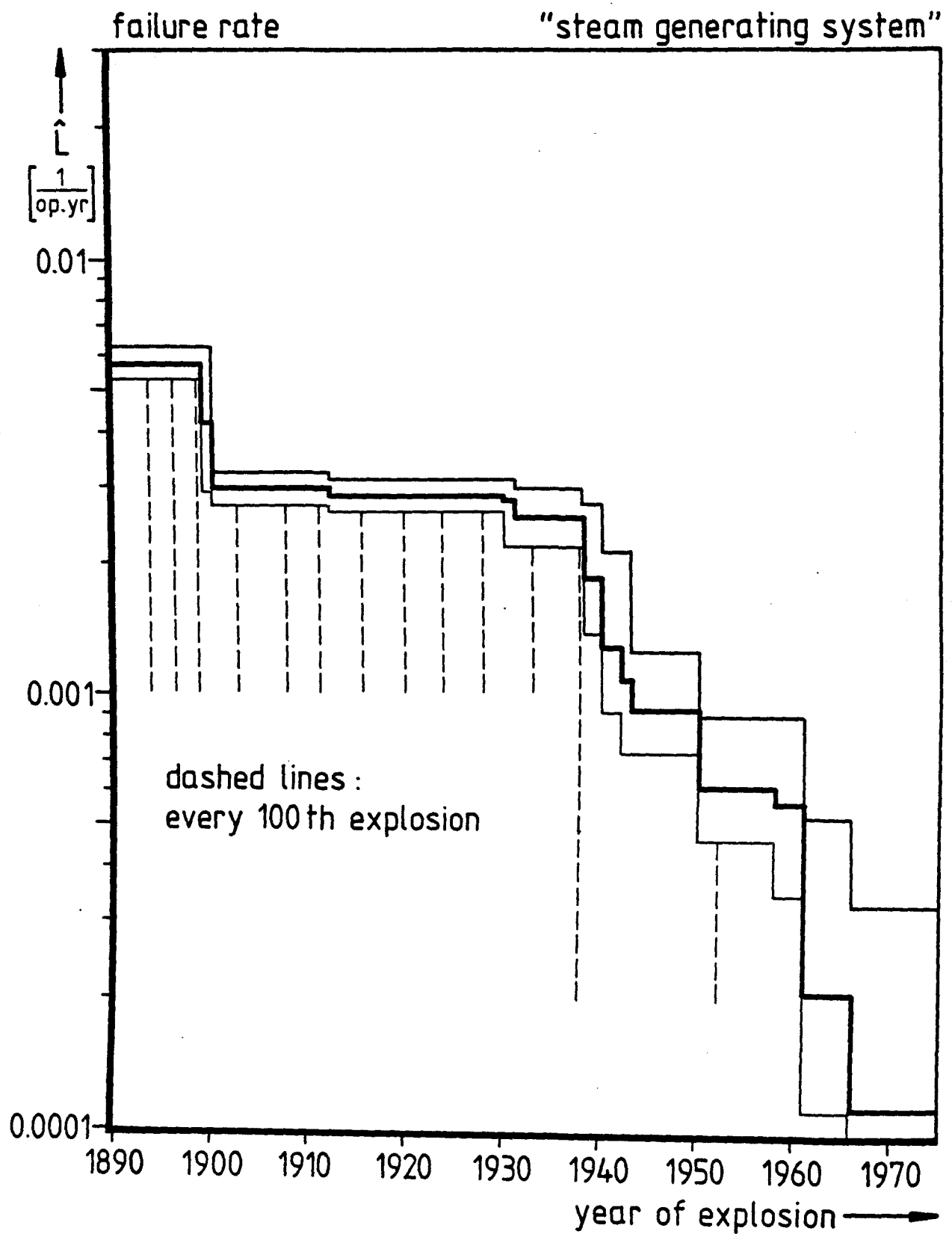


Fig. 3: Failures of the "steam generating system" on British steam and motor ships, isotonic estimate  $\hat{L}$  of failure rates per ship-year, with 90 % confidence intervals

remaining 88 cases are failures in various parts of the system and by various causes.

The analysis of the explosions of main boilers reveals a significantly declining frequency as shown in Fig. 4. The general trend is quite similar to the overall trend depicted in Fig. 3; however, the confidence band toward the end of the observation period becomes much larger to the extent that a trend significance on the 90 % level cannot be established after the Second World War. The failure rates are related to operation-times of steam ships; they therefore represent failures of the "propulsion steam generating system" of a steam ship.

The reports of the Board of Trade differentiate further with respect to causes for the explosions:

1. deterioration of corrosion
2. defective design or undue working pressure
3. water hammer action
4. defective workmanship, material or construction
5. ignorance or neglect of attendants
6. miscellaneous

As the most frequent causes within these categories are noted (the number of main boiler failures is given in parenthesis):

- to 1) internal corrosion, corrosion from leakage, gradual development of a crack (460 cases);
- to 2) joint of manhole door improperly made, manhole door fitted badly, and undue working pressure (21 cases);
- to 3) the cause rarely noted (therefore it is not included in the analysis below) (1 case);
- to 4) (overlapping with 2) badly fitting manhole door, unsuitable jointing material (of manhole door joint), defective welding (131 cases);
- to 5) overheating through deposit of salt or scale, or through shortness of water due to neglect of attendants (195 cases).

Of the 845 failures of main boilers, 37 cases are then in category 6.



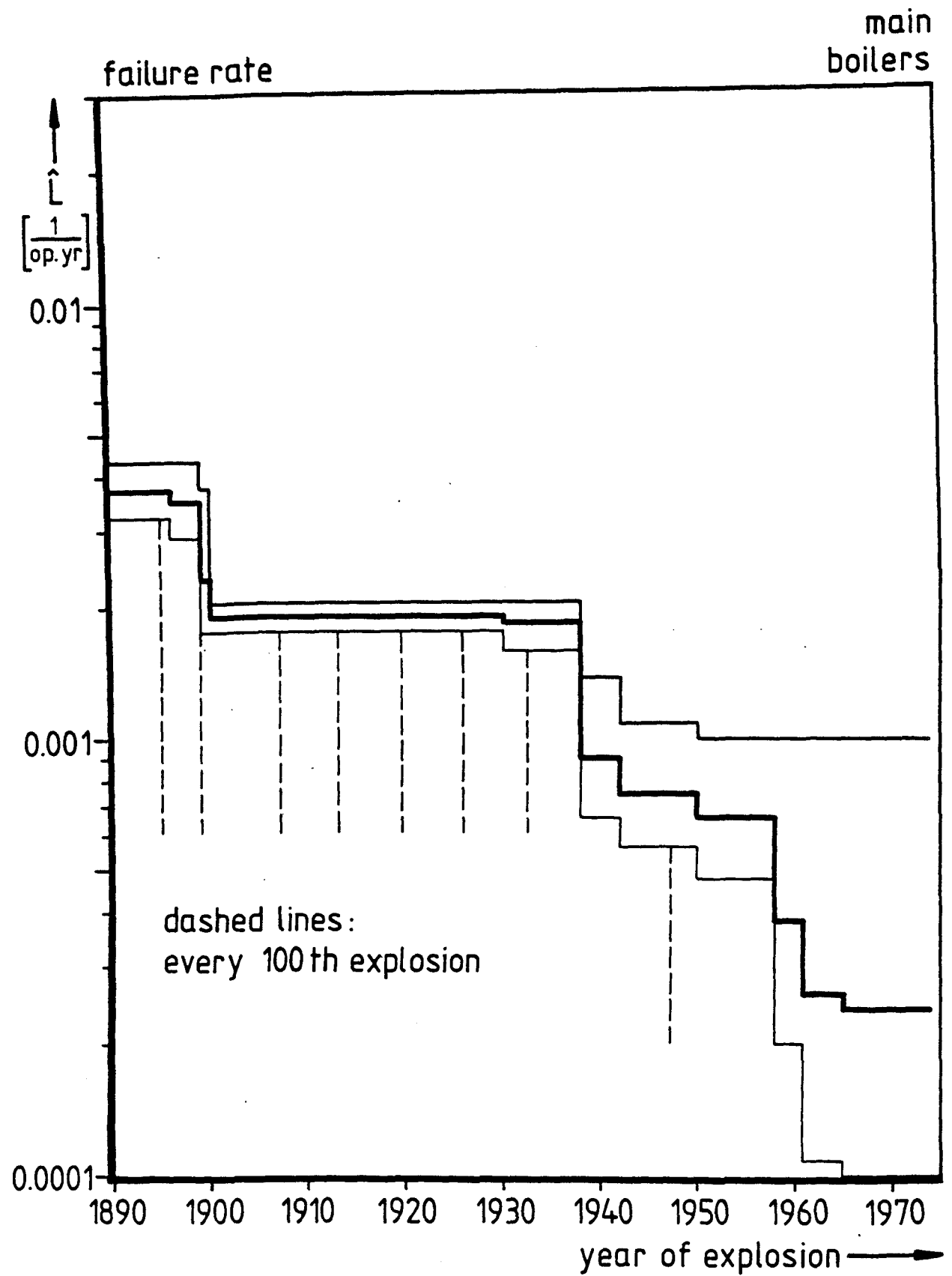


Fig. 4: As in Fig. 3. Failures of the "steam generating system for propulsion" (failures of main boilers)

Figure 5 depicts the failure trends in the four damage categories 1, 2, 4 and 5. (The analysis method is the same as above.) These trends show some noticeable differences:

The trend for the category 1 is similar to the overall trend since this category contains about 55 % of all failures. Category 2 shows a significant decrease already prior to the First World War, nearly down to the recent frequencies; i.e. design errors have been eliminated quite early. Less fortunate is the development of cause-category 4, for which the quality of the materials plays an important role. Practically no significant decrease is indicated for category 5; i.e. human error as cause of failures has not decreased since the beginning of the century. This also means that the design has not become more forgiving to operator errors.

In addition to main boilers, damage to the main steam pipes and stop valves are investigated, since they are part of the propulsion system and also have a high failure frequency. Figure 6 shows the two trends. Since steam pipe ruptures are mainly due to design errors and material problems, the failure frequency trend is between the category 2 and 4 trends for the main boilers. The decrease over the observation period is highly significant; this does not appear to be the case for the stop valve failures. It should be noted, however, that between 1941 and the end of the observation period (1974), there is only one stop-valve failure so that the 90 % confidence interval is quite broad.

The trends above are analyzed in terms of failures per ship or per propulsion system. Two alterations of the analysis come readily to mind, although additional information would be needed for it:

One would be the relation of failures to the operation time of boilers instead of ships. With the number of boilers per ship decreasing in the long run, the resulting trends would be decreasing less than found above. This, however, would not be entirely fair, since the power output of the individual boilers has increased along with the reduction in their numbers. In this comparison, the trend would even be stronger declining since the power of the steam ships has increased considerably. So, relating the failures to ship operation years, an approach that is suggested by the lack of other data, appears to be a good compromise.

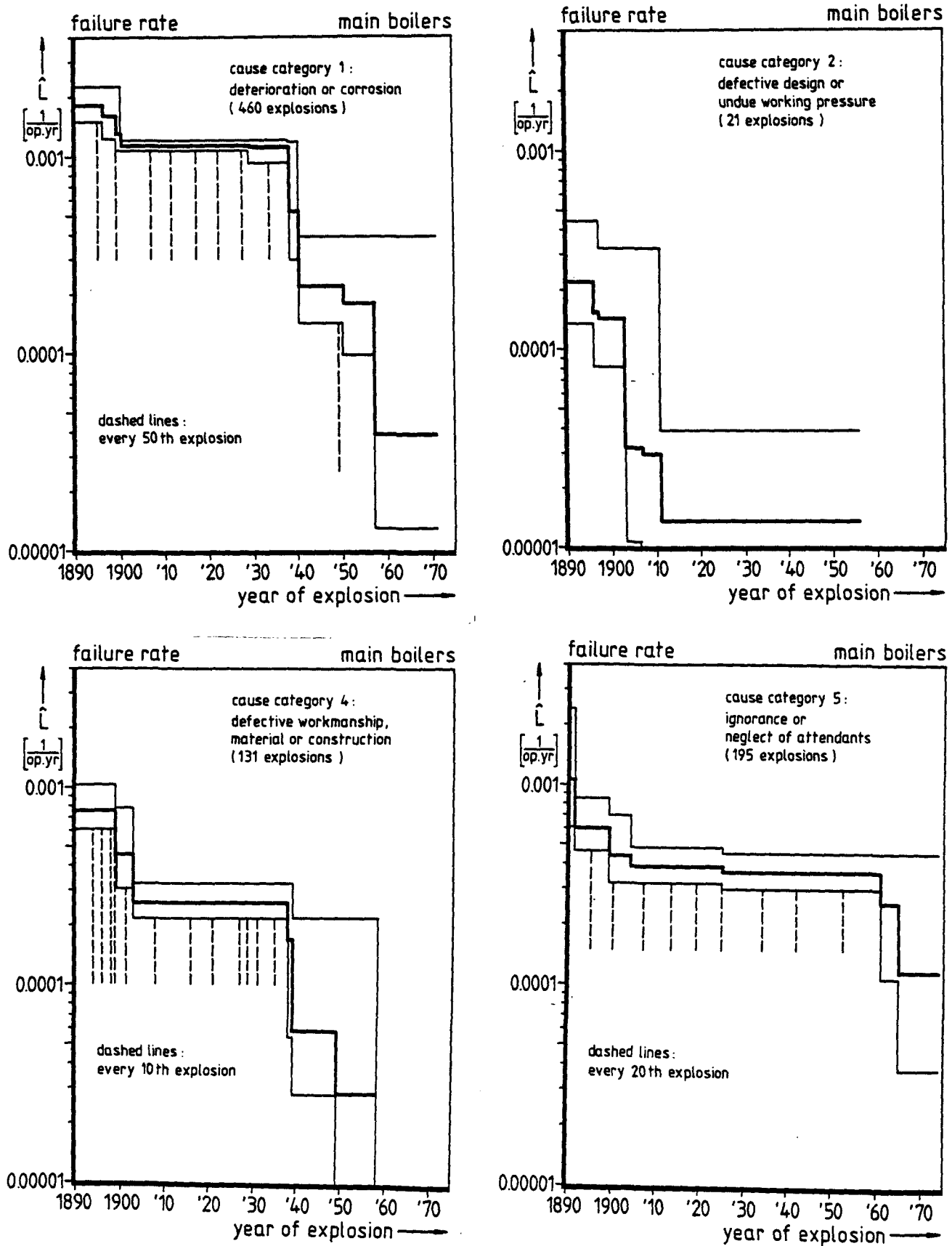


Fig. 5: As in Fig. 4. Main boilers by causes of failure.

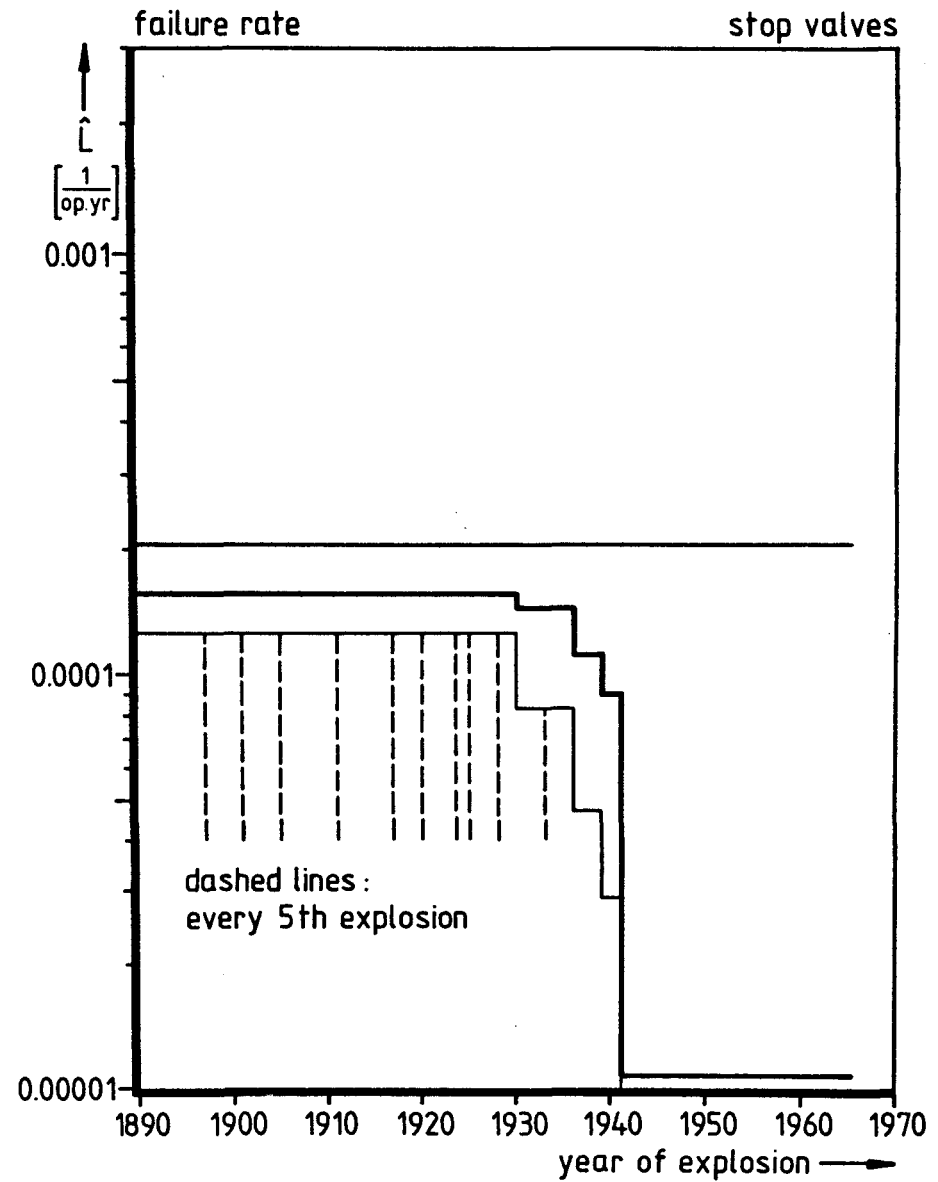
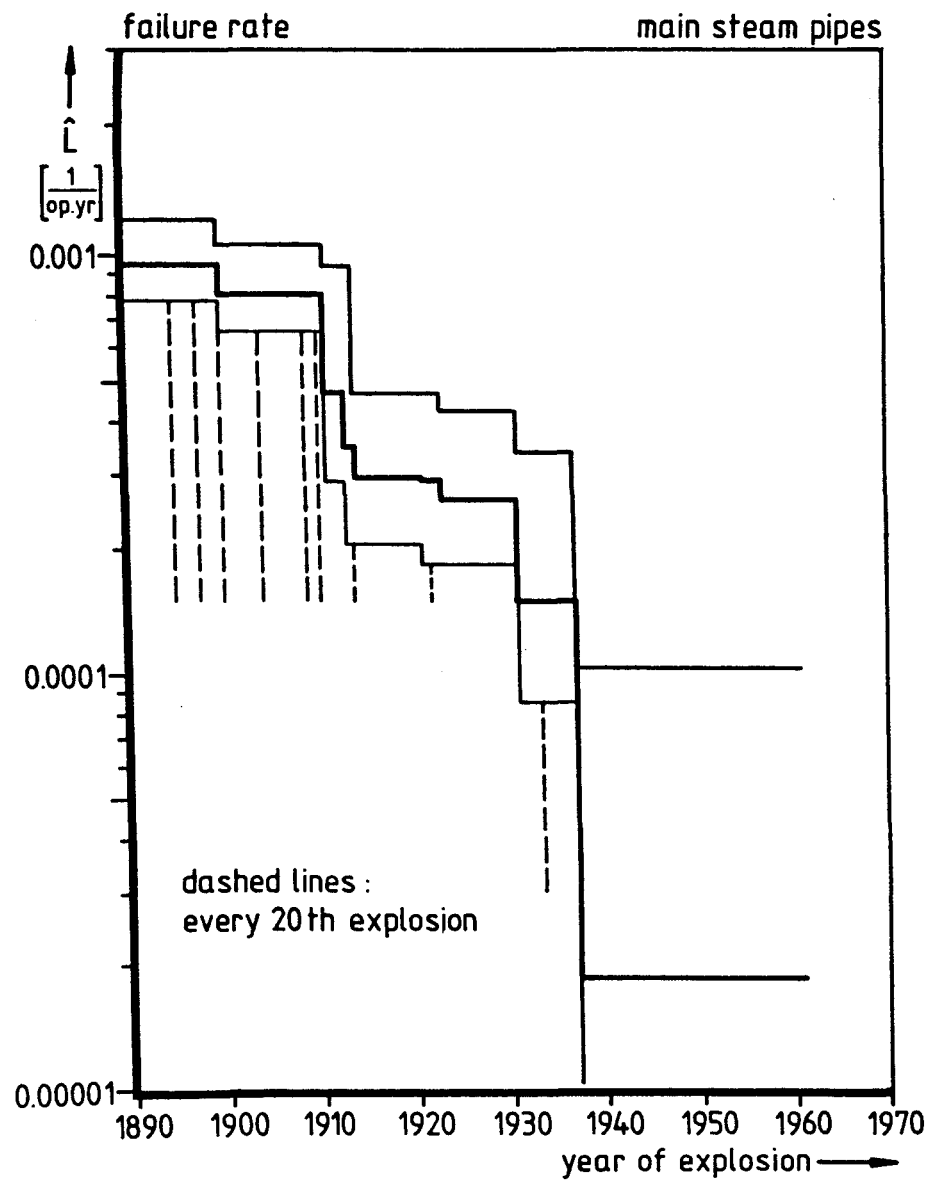


Fig. 6: As in Fig. 4. Failures of main steam pipes and stop valves.



### Construction Year and Age Dependencies

In Ref. 4 the "failure ratio",  $S(t^C)$ , was introduced as a measure of the safety performance of technical units built in the construction year  $t^C$ . It is the probability for a unit to have a major failure during its useful life, or up to a designated maximum age. Here, the age of steam ships considered in this analysis is limited to 50 years. Unfortunately, the performance of boilers, for which the explosions have been analysed above, cannot be evaluated in these terms, since the information on their construction rate is not available.

However, there is a combined quantity, for which the term "marginal failure potential",  $P(t^C)$ , was coined in Ref. 4, that can be extracted - in a first approximation - directly from the available data.  $P(t^C)$  is equal to the product of the failure ratio times the construction rate. Let  $P_1(t^C)$  denote the first approximation of  $P(t^C)$ , that evaluates the failures of technical units built in  $t^C$  between  $t^C$  and the end of the observation period, as opposed to  $P(t^C)$ , that pertains to the same designated period (here 50 years) for all  $t^C$ . Thus  $P_1(t^C)$  is equal to or smaller than  $P(t^C)$ , the more so the shorter the observable age span. The deviation between  $P_1$  and  $P$ , however, is quite small for the main-boiler explosions analysed here (see below), and therefore  $P_1$  is used instead of  $P$  in the following.

In the evaluation of a possible trend in  $P_1(t^C)$  the statistical fluctuations need to be reduced by considering larger time intervals. There apparently is an optimum time-interval structure between the two extremes, i.e. between the minimum (annual) interval size, for which the trend is disguised by the large fluctuations of the small number of failures per interval on the one hand, and the maximum interval size, the entire observation period, for which the statistical fluctuations are smallest, but the trend information is totally lost. In the presented analysis, the interval structure was optimized by the criterion of finding the maximum number of intervals for which an overlap of the 90 % confidence intervals (corresponding to  $1.64 \sigma$ ) is just avoided, since a lack of that overlap establishes significance of the trend. In general, if a trend is identified by this method on a high level of significance, it can be assumed to exist in actuality; i.e. the demonstrated statistical significance is a sufficient

criterion for the existence of a trend. However, it may not be a necessary criterion, i.e. a trend could well be present without demonstrated statistical significance, e.g. when the intervals are improperly chosen.

Figure 7 presents  $P_1(t^C)$  for main boilers, calculated as described above. The interval optimization procedure yielded six  $t^C$ -intervals for which the confidence intervals are comfortably separated, by  $2.34 \sigma$ , rather than the minimum of  $1.64 \sigma$ . (For seven  $t^C$ -intervals, the maximized minimal confidence band separation would have been smaller than  $1.64 \sigma$ ).

As shown in Ref. 4, there is a convolution-integral type relation between  $P(t^C)$  and the failure rate at time  $t$ . This relation is particularly simple for accidents due to design errors and faulty construction, since the corresponding failures have the tendency to occur early in the life of the affected units. Then, the failure rate "follows" the marginal failure potential with a characteristic time delay. In order to show this, the failure rate of main boilers, as obtained above, per operation year was approximately converted in a rate per calendar year by multiplication with the number of steam ships in operation (small circles in Fig. 7).

The informative value of  $P_1(t^C)$  for these boilers is limited since it largely expresses the strong reduction of steam-ship construction over the recent few decades (see also Fig. 2). More informative is the age dependency,  $M_1(\tau)$ , of the failure events, where  $\tau$  denotes the age.  $M_1(\tau)$  is defined as the sum of all actuarial explosions in ships of age  $\tau$  in the considered population. The index "1" again suggests an evaluation in a first approximation that here pertains to the consideration of the average ship-age dependency of the explosions for all construction years in the data base,  $M(\tau)$ . It can be shown that in the discussed example  $M_1(\tau)$  only slightly differs from  $M(\tau)$ . Therefore  $M_1$  that can be directly extracted from the data is used instead of  $M$  in the following.

Figure 8 shows this approximate age distribution,  $M_1(\tau)$ , of failures, for nine age-intervals. The 90 % confidence intervals do not overlap; so there is a significant trend of  $M_1$  with increasing age,  $\tau$ , on the 90 % confidence level. It appears that  $M_1$  shows at first a significant increase by about a factor of four, leading to a maximum around an age of 10 years; this could be related to material problems, such as corrosion and fatigue

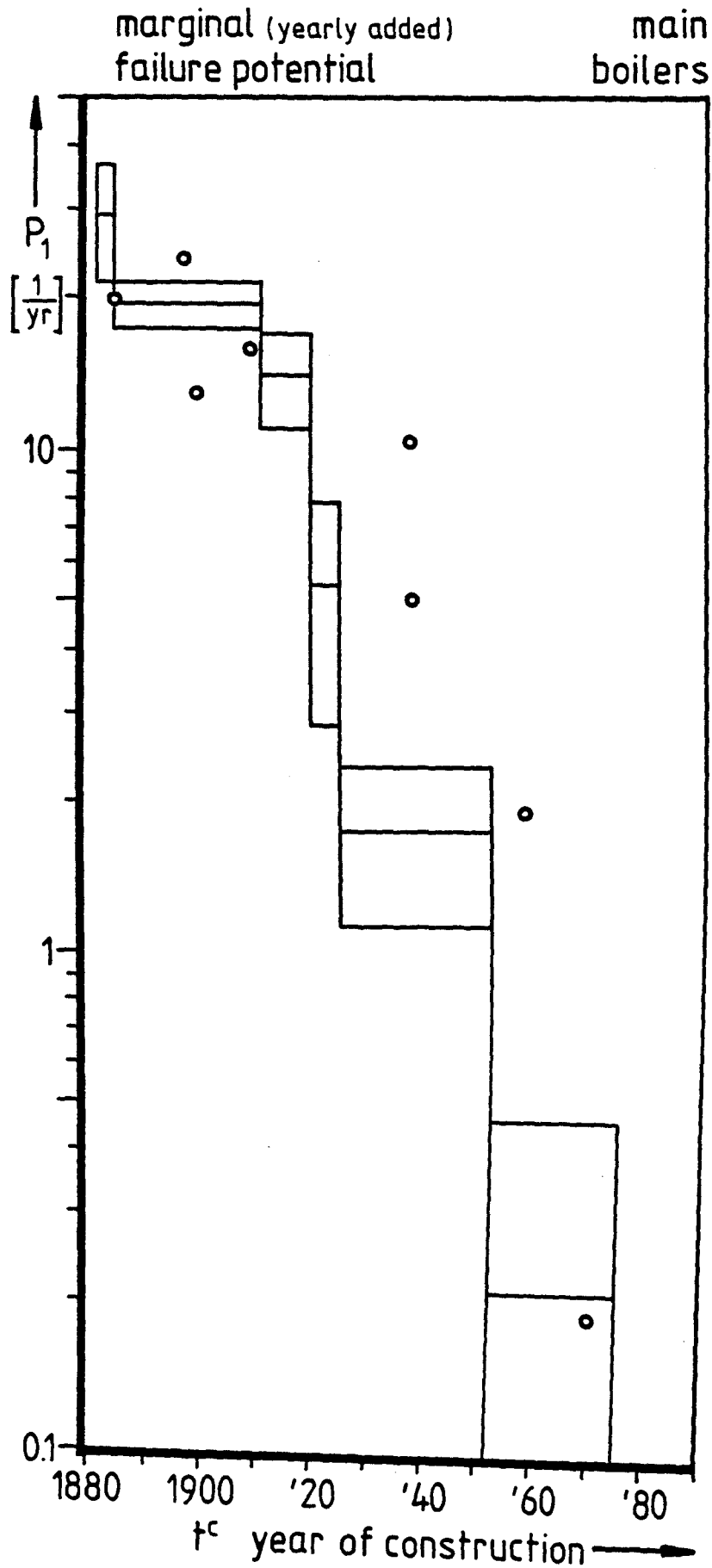


Fig. 7: Main boilers on British steam ships. Failure potential dependent on year of construction. Circles: Actuarial failure rates (isotonic estimate) for comparison. 2.34 -  $\sigma$  confidence intervals (i.e. > 90 %).

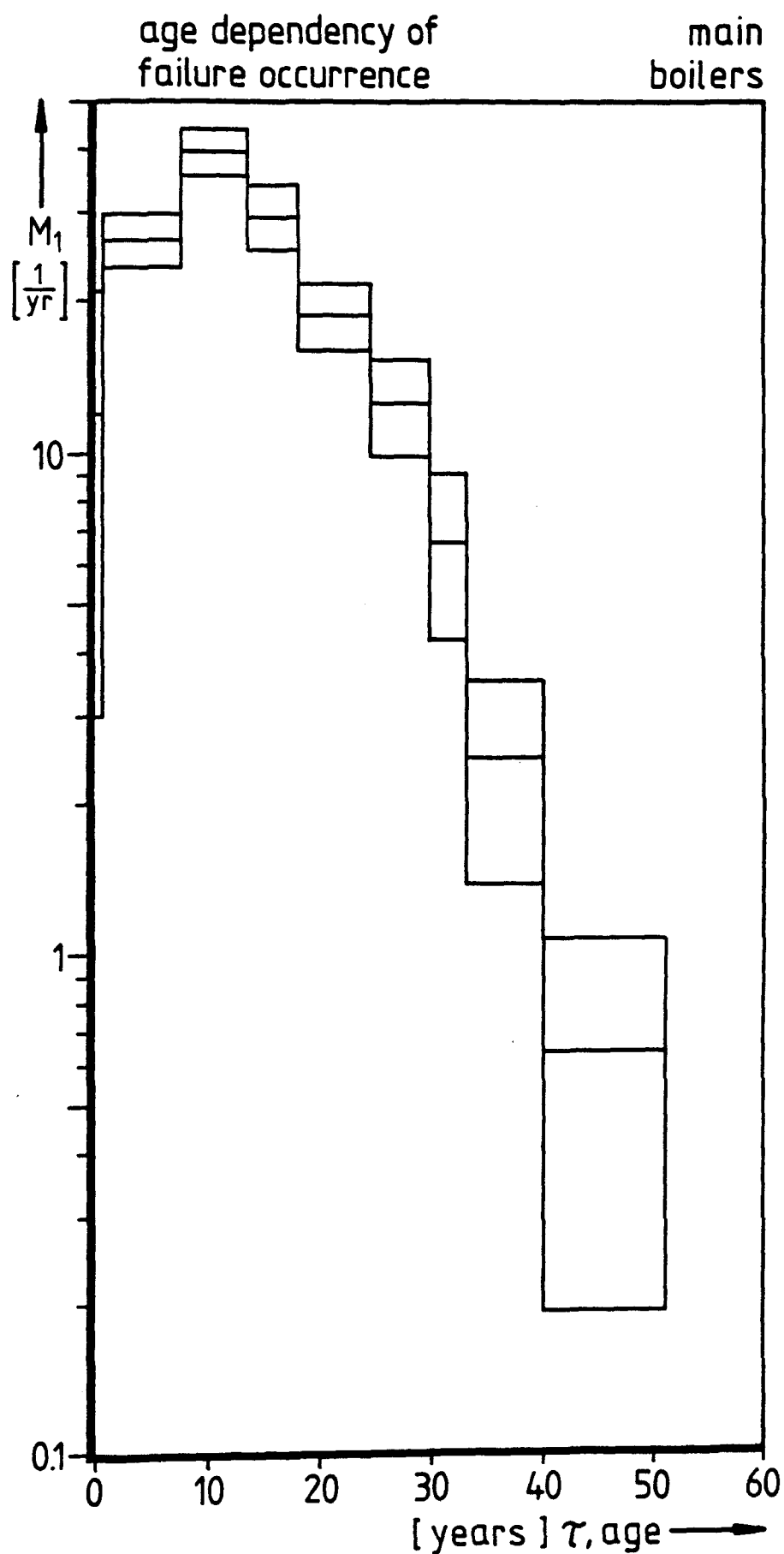


Fig. 8: Main boilers on British steam ships. Age dependency of failure occurrence. With 1.64  $\sigma$  (i.e. 90 %) confidence intervals.

effects. Subsequently,  $M_1(\tau)$  decreases by about two orders of magnitude, that may be partly due to the smaller number of units with larger age.

The data base for the analysis of the age distribution of main-boiler explosions consists of 799 cases. (The difference to 845 cases noted earlier is due to the deletion of steam ships that are older than 50 years and/or are built before 1882). This rich data base provides the opportunity to search for a possible construction year dependency of  $M(\tau)$ . For this, two construction year intervals are considered: 1882 - 1899 and 1900 - 1974. Both groups contain about the same number of explosions. Figure 9 presents both sets of  $M_1$ -values, with solid lines for the first and dashed lines for the second. The same set of age intervals was used for better comparability. Apparently, most of the 90 % confidence intervals about these two sets of  $M_1$ -values overlap substantially, as indicated by the hatched areas. Therefore, the differences between  $M_1(\tau)$  in the last century from the corresponding values in this century are not statistically significant, at least not on the 90 % level. Still, there appears to be the tendency that for the more recent group, boiler explosions occur later in their life than for the earlier group, an effect that could be due to fewer design-error related failures and due to better materials.

In Ref. 4, a method was developed that allows an evaluation of the failure ratio,  $P(t^C)$ , and of the age dependency,  $M(\tau)$ , given  $P_1(t^C)$  and  $M_1(\tau)$ . They pertain to the same designated maximum age, say  $\tau_S$ . That requires a completion of the actuarial information contained in  $P_1(t^C)$  and  $M_1(\tau)$ , by failures to be statistically expected in units that have not reached the age  $\tau_S$ . If however,  $M_1(\tau)$  and  $P_1(t^C)$  are strongly decreasing, as it is the case for the boiler explosion data analyzed here, and if the observation period is much larger than  $\tau_S$ , the completion procedure yields only a minimal addition; here about 4 explosions as compared to the 799 actual events. Then,  $P(t^C) \approx P_1(t^C)$  and  $M(\tau) \approx M_1(\tau)$  as was assumed above.

The previous categorization with respect to causes of failures has been extended to the investigation of the corresponding age distributions (see Fig. 10): the fatigue and corrosion related categories 1 and 4 show a maximum around age 10, that is also reflected in the overall  $M_1(\tau)$ . The design-error related category 2 appears to have its largest occurrence rate at the beginning, although the number of cases is too small to

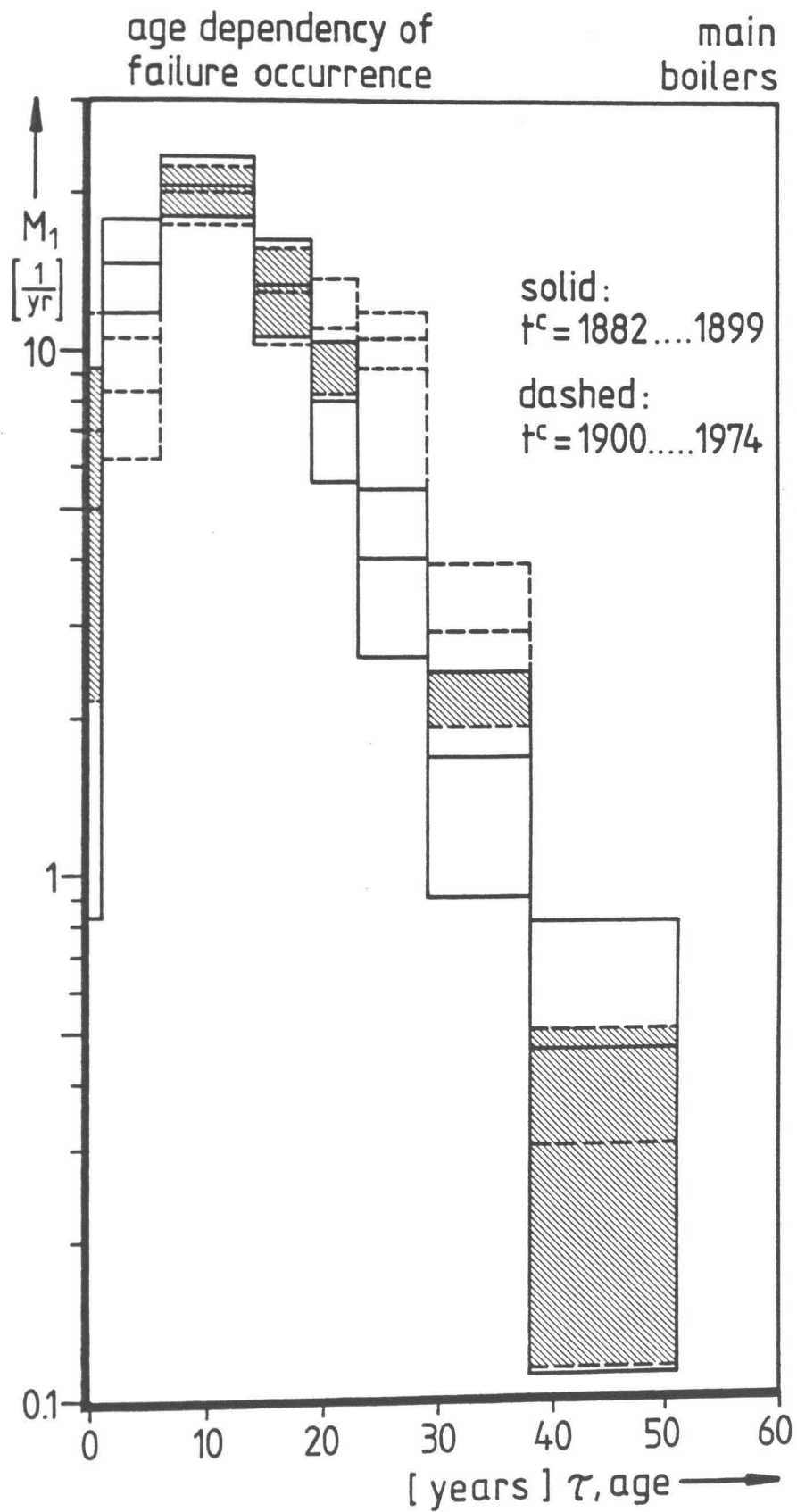


Fig. 9: As in Fig. 8. Comparison of two construction year intervals: 1882 - 1899 and 1900 - 1974. 90 % confidence intervals.

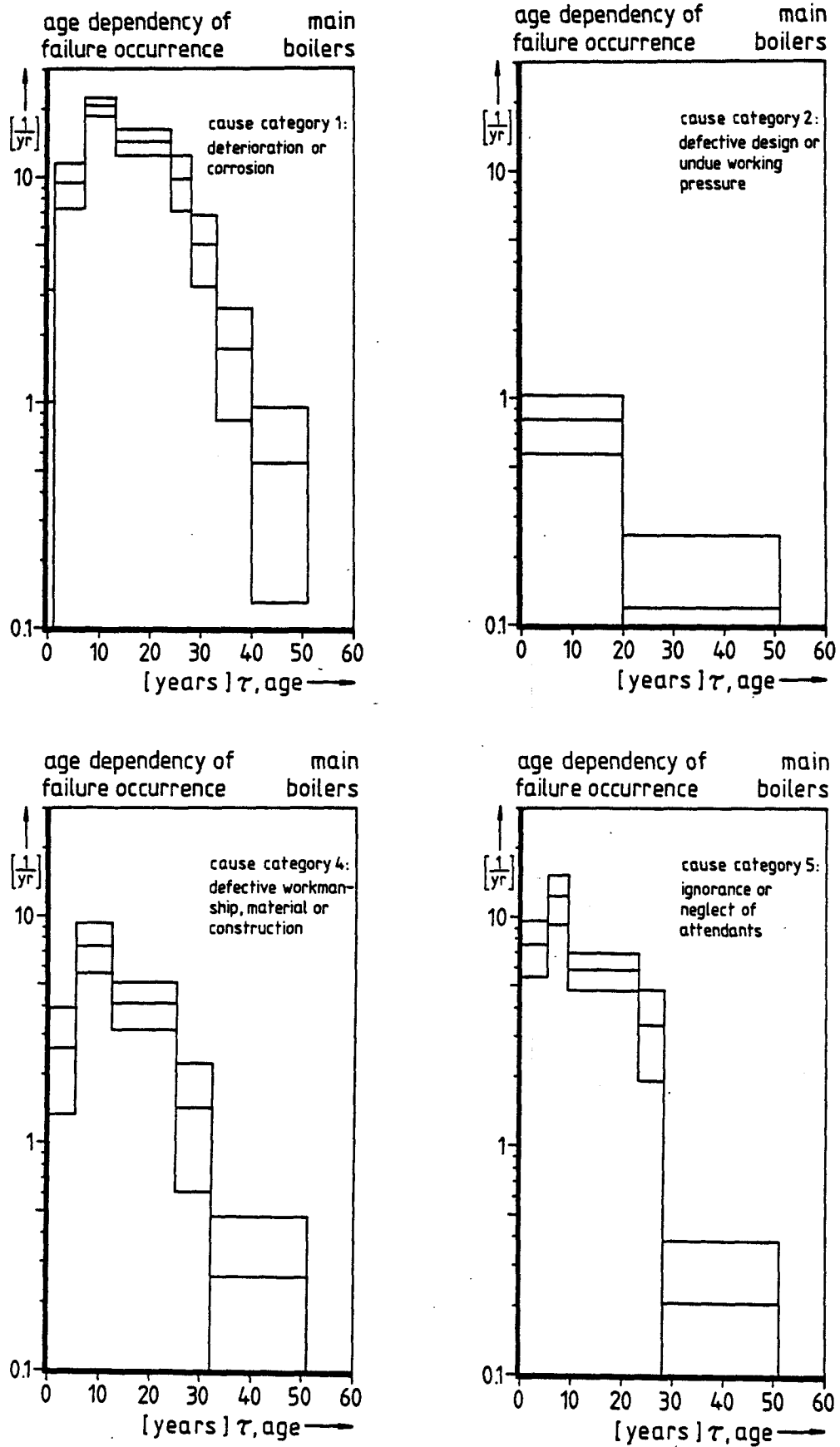


Fig. 10: As in Fig. 8, by causes of failures. With 90 % confidence intervals.



establish a high-level statistical significance. The category 5 events (human error) appear to have a maximum around 6 to 7 years that could be due to a gradual build-up of system deficiencies resulting from inadequate maintenance, e.g. leading to deposits of salt or scale. The decrease after about 20 years of age is apparent in the four categories as well as in the total  $M_1(\tau)$  to various degrees. This could in part be due to an elimination (through explosions) of units with design flaws, poor construction, or due to inadequate maintenance, leading to an increased level of safety in the remaining population. The main cause for the decrease in  $M_1(\tau)$  should be that older units are decommissioned for various other reasons. Thus,  $M_1(\tau)$  pertains to a strongly decreasing population at higher age.

#### IV. STEAM SHIPS FROM LLOYD'S REGISTER, 1960 - 1968

##### Introductory Remarks

The steam ship data analyzed in this section have been assembled by Lloyd's Register in a special contract study (Ref. 8). The statistical analysis is methodologically the same as above; however, there are a number of remarkable differences so that the results are not directly comparable:

- The failure data pertain to a different ship population, generally newer ships of international fleets. The ships in Lloyd's Register represent about one third of the world's commercial fleet.
- Also fire box explosions are considered which - as discussed above - appear to be the predominant causes of failures in recent years. This is primarily a new category of problems, resulting from control and the use of highly explosive fuel rather than from design or materials. These fire box explosions are explicitly excluded from the Board of Trade reports discussed in Chapter III.
- The failure rates are related to operation years of boilers rather than of ships, since the number of boilers at risk is available.
- Since also the construction rate is known, the failure ratio  $S(t^C)$ , can be calculated.
- As opposed to the British steam ships investigated above, one does not deal here with a strongly declining population (see Fig. 11). Whereas the main boilers are used exclusively aboard steam ships, auxiliary boilers are used also on motor ships that dominate in the recent decades.
- Because of the short observation time interval, a completion of  $P_1$  and  $M_1$  by explosions that are statistically to be expected in the future is required to find the construction year and age dependencies,  $P(t^C)$  and  $M(\tau)$ , of the safety performance. The completion provides in this case a substantial contribution, contrary to Section III.

number of boilers at risk  
in ships of Lloyd's Register

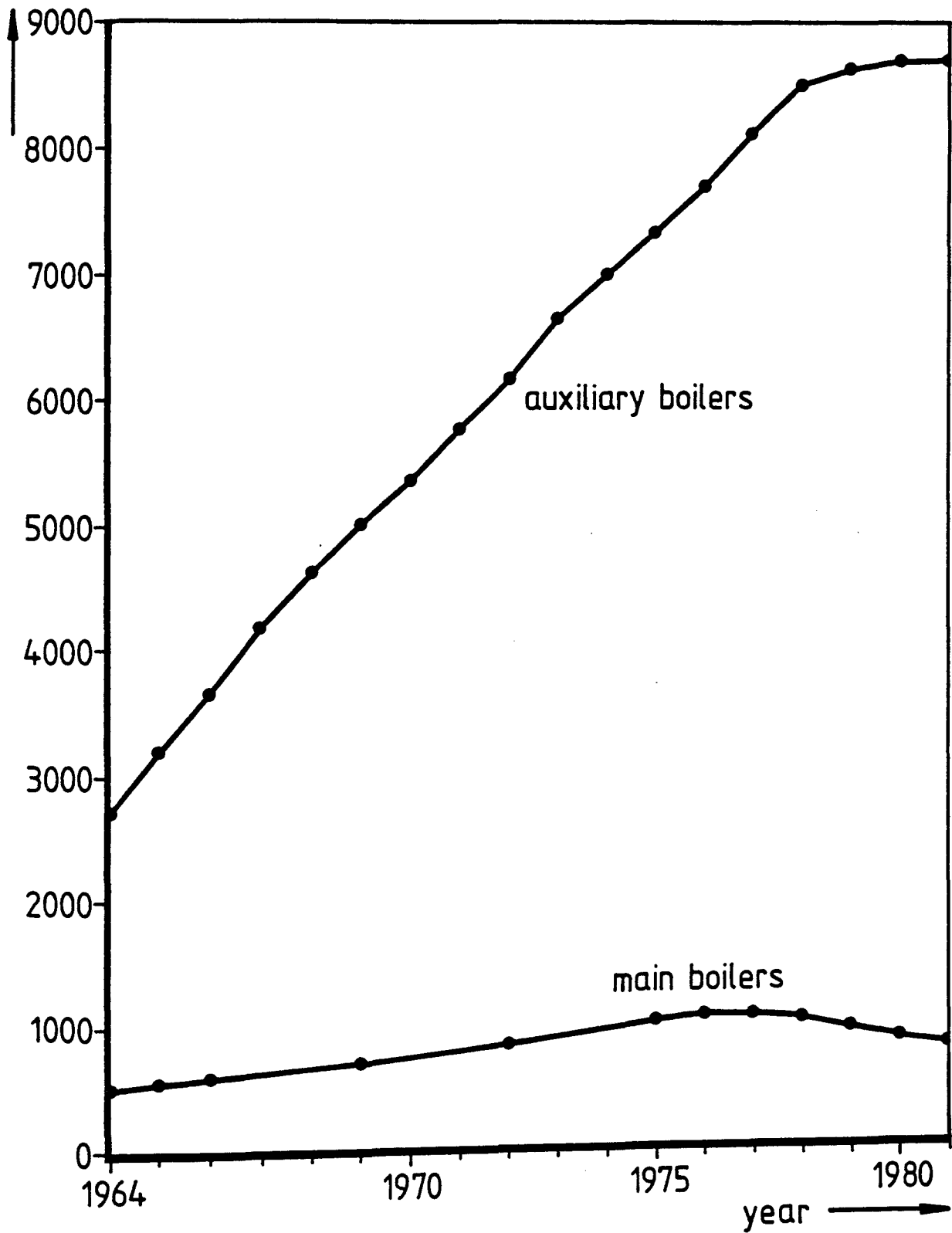


Fig. 11: Ships (steam and motor ships) of Lloyd's Register. Number of boilers at risk (after Ref. 8).

### Trends of Failure Rates

The trends of boiler failure rates were analyzed in the same way as in the previous section by applying isotonic regression to the spacings between failure events, here measured in boiler-operation years. The resulting monotonous frequency trend is depicted in Figs. 12 and 13 together with the 90 % confidence intervals. The main-boiler analysis, Fig. 12, is based on 31 failures that occurred between 1968 and 1981 in ships constructed since 1960. The auxiliary boiler failures in Fig. 13 show the trend of the 97 failures recorded for the years 1960 through 1981 in ships constructed since 1960. The main boilers show no significant trend, this is not surprising because of the small time interval. The longer series for auxiliary boilers however shows a significant decrease in its failure rate. The values for main boilers are higher than for auxiliary boilers, probably because of the more difficult operation of the much larger fire boxes.

### Construction Year and Age Dependencies

In the same way as in Section III were the failure data combined in intervals to yield approximations for the failure potential,  $P_1(t^C)$ , on the one hand and the age dependency,  $M_1(\tau)$ , on the other. Since for the Lloyd's data, the (annual) construction rates are known, the approximate failure ratio,  $S_1$ , can be determined, too. However, over the short observation periods, neither  $P_1$  nor  $M_1$  decrease very much. Therefore, the completion procedure developed in Ref. 4 needs to be applied to obtain a meaningful characterization of the safety performance by the completed values  $S(t^C)$  and  $K(\tau)$  - the latter of which is the normalized  $M(\tau)$ . This requires the solution of an integral equation as described in Ref. 4. The result indicates that 14 explosions of main boilers should be statistically expected in addition to the 21 that have occurred in the past, in units constructed since 1968 (see Fig. 14), whereas the auxiliary boiler analysis adds 26 failures to the actuarial number of 97 events in units constructed since 1960 (see Fig. 15). The corresponding rise of  $S$  as compared to the actuarial-data based approximation,  $S_1$ , is clearly apparent in Figs. 14 and 15.

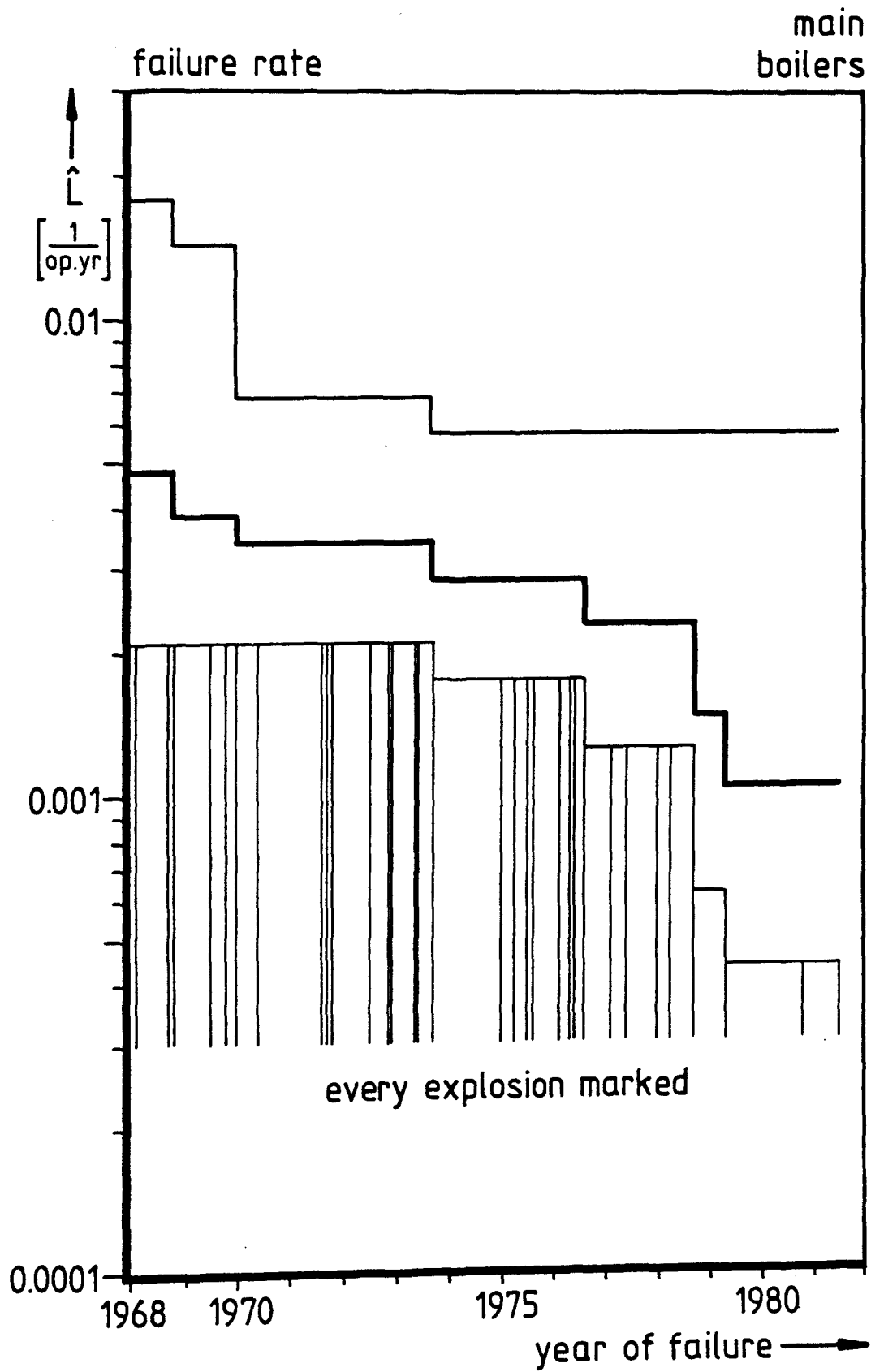


Fig. 12: Ships of Lloyd's Register. Isotonic estimate of failure rates per boiler year. Main boilers. With 90 % confidence intervals.

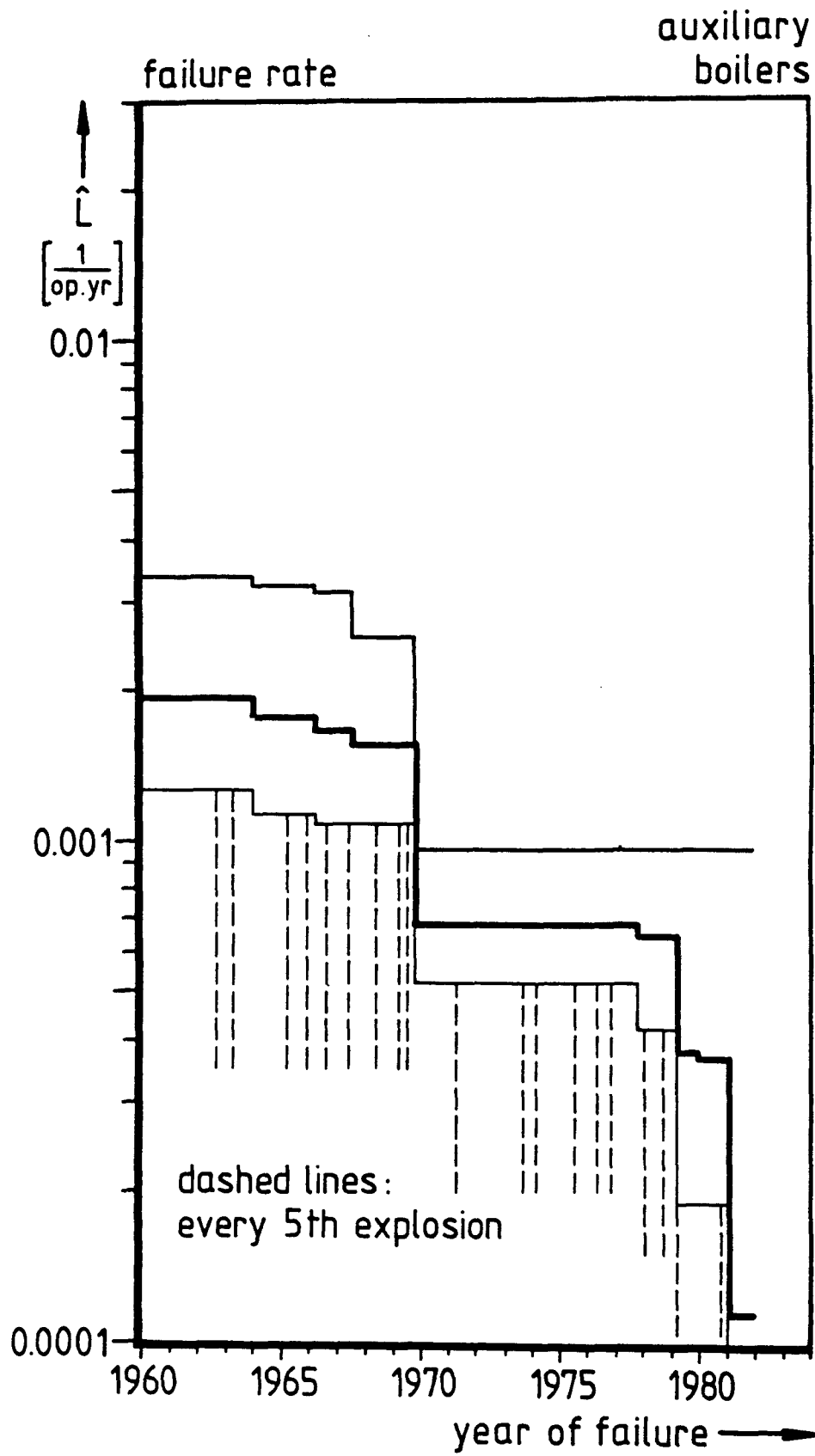


Fig. 13: As in Fig. 12. Auxiliary boilers.

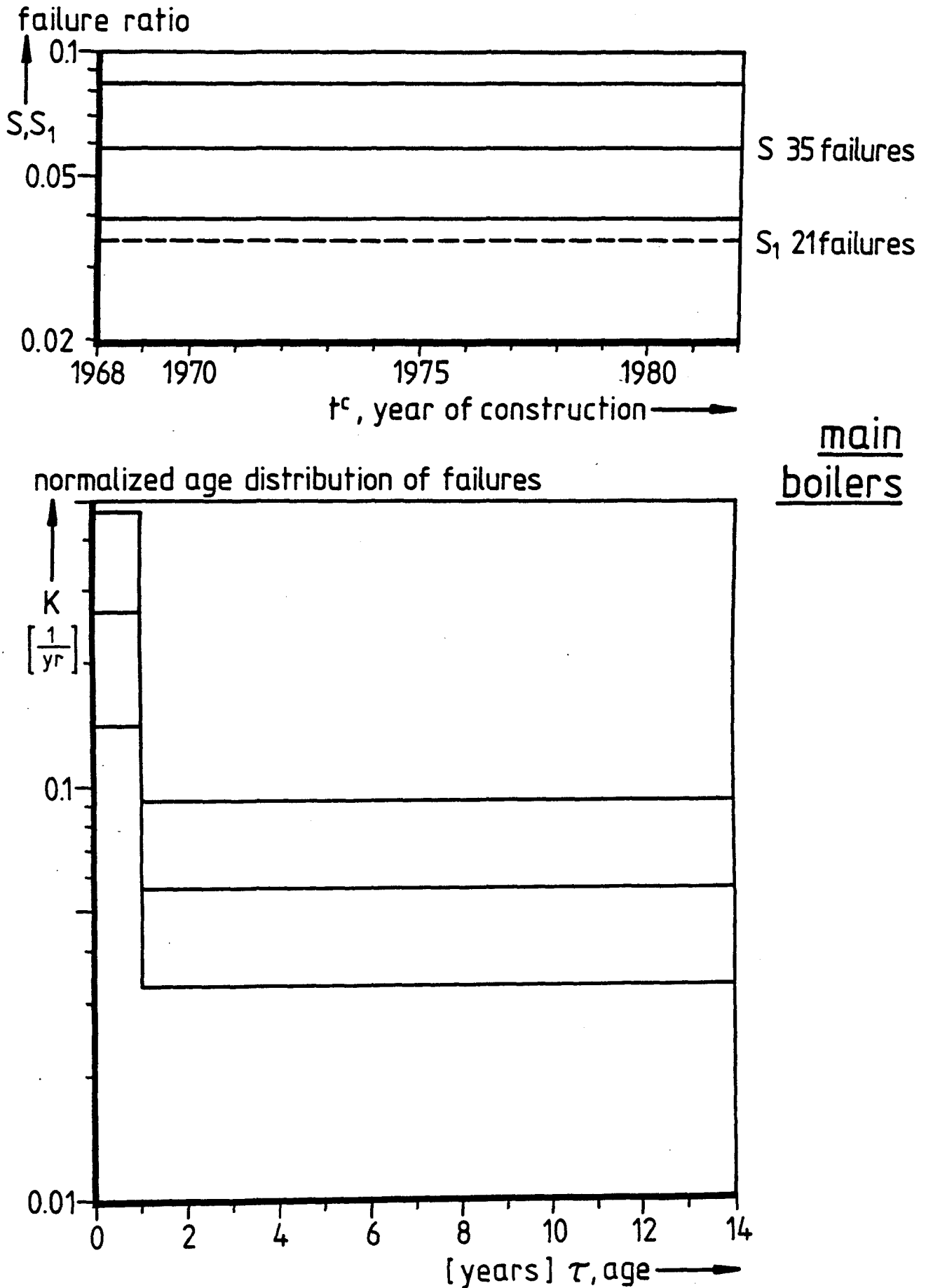
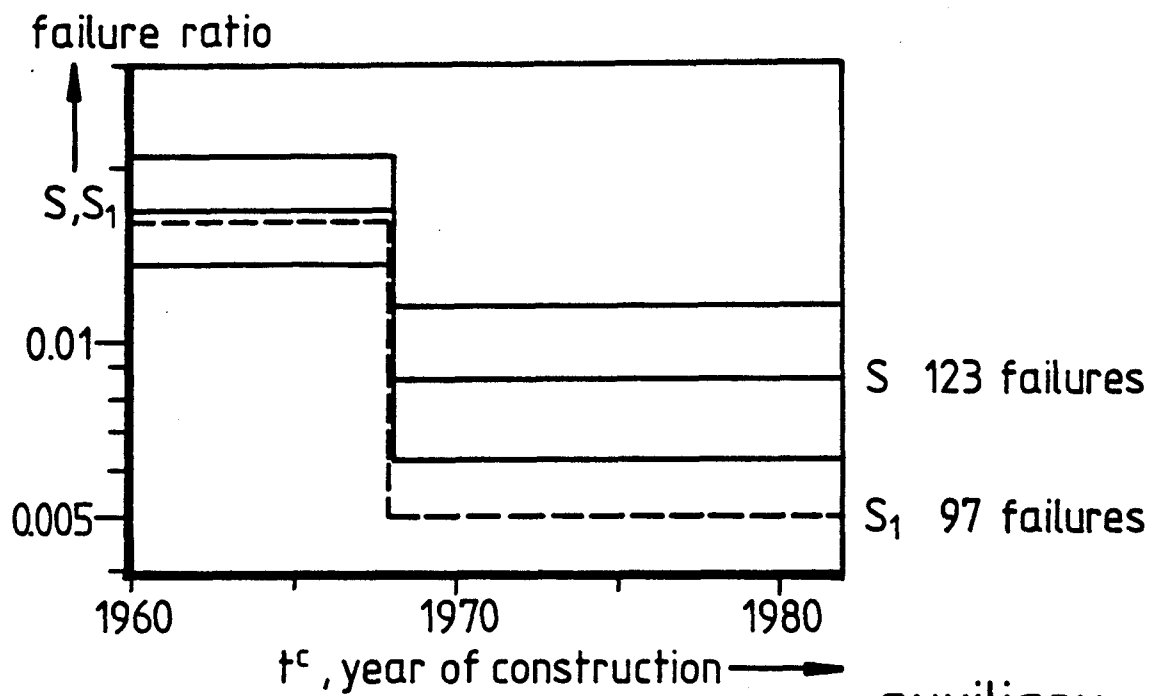


Fig. 14: Ships of Lloyd's Register. Main boilers. Failure ratio,  $S$  (compared with the uncorrected value  $S_1$ ), and normalized age distribution of failures,  $K$ . With 90 % confidence intervals.





auxiliary  
boilers

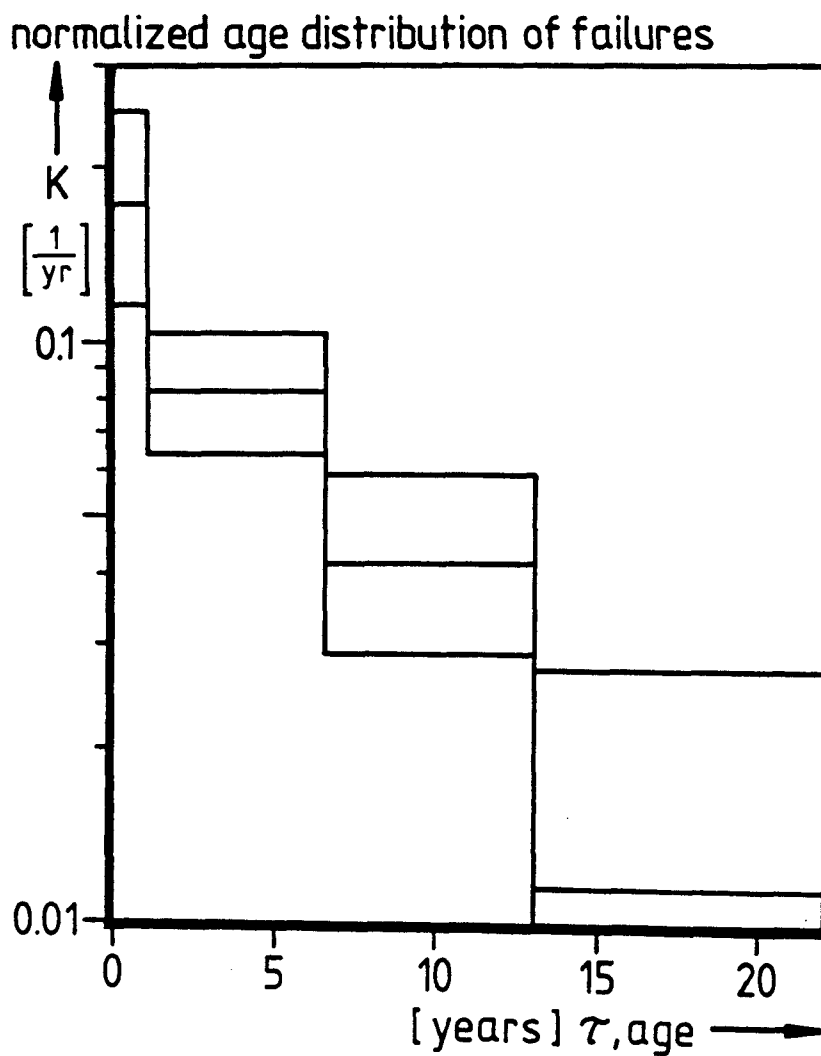


Fig. 15: As in Fig. 14. Auxiliary boilers.

The relative completion naturally increases with  $t^C$ , because an increasing fraction of the useful life lies in the future. The rise of  $S_1$  into  $S$  in auxiliary boilers (Fig. 15) amounts to about 70 % at the end of the observation period as compared to only 5 % at the beginning.

The time span for the main boiler data (Fig. 14) is so short that a partitioning of the  $t^C$  period in several intervals did not appear to be useful. (The level of significance of the trend of  $S$  would be much less than 90 %.) Therefore, the data were analyzed in toto, yielding an addition of 35 failures to be statistically expected as compared to the 21 actuarial events. The increase in  $S$  as compared to  $S_1$  is assessed only on the average, amounting to about 70 %.

Both main and auxiliary boilers show a 90% significant decrease of the normalized age distribution,  $K(\tau)$ , within 14 resp. 22 years of age.

## V. SUMMARY

This paper begins in Section II with a description of the technological development of boilers aboard steam ships, emphasizing the evolutionary improvement of their safety as well as economic performance. The latter appears in terms of thermodynamic efficiency and overall power output, the former in terms of a reduction in the frequency of boiler explosions.

The discussion of the evolution of safer boilers aboard steam ships is complemented by a statistical analysis of a long series of observations (and descriptions) of explosions aboard British steam ships from 1882 through 1974 in Section III, as recorded by the Board of Trade. The number of steam ships covered in this statistic increased at first, reached a maximum of more than 8000 before the First World War and decreased subsequently to about 200 (though much larger) ships today. The major part of the analysis considers the steam generating system for the ship propulsion that includes the main boilers.

The analysis is a search for a trend underlying the statistically fluctuating temporal spacings between the explosion events. The results are expressed in the form of a sequence of failure rates per ship-year of operation. Apparently, there is a strong and statistically highly significant declining trend of the failure rate, beginning with about one explosion per 250 ship-years to less than one per 2500 ship-years toward the end of the observation period (1974).

In addition, trends of failure causes were analyzed: Design-error related explosions receded strongly already around the turn of the century. The frequency of material and construction related causes shows two periods of stronger declines, one around the turn of the century and one before the Second World War. Human error as a cause of failure shows no significant decline over the entire period; i.e. the design did not become more forgiving.

The analysis of the age dependency of the failure occurrences exhibits a strong decrease after about 10 to 15 years, following an earlier increase that is probably due to material- and age-related problems as well as inadequate maintenance.

Furthermore, a larger and newer ship population, from Lloyd's Register, was investigated in Section IV where the failures also included gas explosions in fire boxes (that are excluded in the Board of Trade reports). Though the observation periods are much shorter (1960 through 1981 for auxiliary boilers, and 1968 through 1981 for main boilers), information on the number of boilers at risk as well as on construction rates was available; this then allowed a more detailed analysis.

The trend analysis of the failure rates, here related to boiler rather than ship-operation years, shows no statistically significant decline over this relatively short observation period for the main boilers. However, some decrease is noticeable between the beginning and the end of the longer observation period for auxiliary boilers. The explosion frequency generally is higher than it appeared for the last years of the British steam ship analysis in Section III, largely due to the inclusion of the relatively large number of fire box explosions.

The availability of construction rate data, in addition to the failure data, allowed a statistical evaluation of the failure ratio, i.e. the probability of an explosion during the useful life of a boiler. This evaluation is possible by a combination with the analysis of the age distribution of failures and its use for a completion of the actuarial data by projecting events that have to be statistically expected in the future. This statistical completion procedure, developed in Ref. 4, yields 14 main boiler failures in addition to the recorded 21 events, and 26 additional failures for auxiliary boilers, as compared to 97 actuarial (past) failures in the evaluated data base.

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